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INVESTIGATION OF  
RF NOISE GENERATION  
FROM SPACE VEHICLES

Final Report  
Contract NAS 8-862

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## FOREWORD

This is the final report on Contract NAS 8-862, "Investigation of RF Noise Generation from Space Vehicles." The work was administered under the direction of the George C. Marshall Space Flight Center, Redstone Arsenal, Huntsville, Alabama.

The studies began in June 1961, were concluded in January 1963, and represent effort of the Electron Dynamics Laboratory of the Hughes Research Laboratories. Dr. J. August, R. D. Wanse-low, and S. L. Eilenberg were the engineers principally responsible for the research activity on this contract.

This report concludes the work on Contract NAS 8-862.

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## ABSTRACT

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This report summarizes the results of studies conducted on the determination of rf noise generation by high beam density electrical propulsion engines. The objective of the program was to determine analytically and experimentally the power spectrum of noise generated by electrical propulsion devices, with emphasis on the cesium contact ion engine being developed at Hughes Research Laboratories. This information is important for the design of flight test telemetry and space vehicle communication systems which require a minimum of interference with on-board space receivers.

Initial effort was devoted to analytical determination of noise generated in neutralized ion beams by various mechanisms. Operating parameters of the plasma engine which affect rf noise were determined, and suitable typical values of these parameters were selected for quantitative calculations. It was also found that a noise growth mechanism may exist under certain beam conditions. Models of the plasma wake were considered and are discussed.

Experimental investigations were made on a typical annular ring cesium contact ion engine over the communications frequency spectrum. The tests yielded no measurable noise output from the ion beam itself, although rf radiation as a result of low level periodic arcing across engine insulators was observed early in the program. However, an improved engine design eliminated this source of radiation. Measurements also were made on the Penning discharge engine, the tests indicating that this type of engine will generate rf noise interference for space communications receivers.

Preliminary conclusions of this study are that communications systems in a space vehicle containing a Penning discharge engine should be operated above the cyclotron and plasma frequencies. In this higher frequency range, there is a reduction in plasma noise and the conductive properties of the plasma will have less effect on antenna patterns.

Author

Communication systems in a space vehicle containing a contact ion engine should not encounter operating difficulties with respect to rf noise; however, a vehicle antenna with poor directivity characteristics may be capable of observing small amounts of rf noise emanating from the ion engine beam.

## I. INTRODUCTION

The primary objective of this study was to determine analytically and experimentally the rf power spectrum of noise generated by electrical propulsion devices, with emphasis on the cesium contact ion engine being developed at Hughes Research Laboratories under Contract NAS 5-517. This information is important for the design of flight test telemetry and space vehicle communications systems which require a minimum of interference with on-board space receivers.

Various mechanisms were considered in an analytical study of noise generated by neutralized ion beams. These mechanisms included electron-ion collisions, acceleration of electrons at the plasma boundary, ion-neutral background atom collisions, cathode shot noise, and ion acceleration. It also was determined theoretically, by use of a simplified plasma model, that a noise growth mechanism may exist in the vicinity of the engine exhaust plane under certain conditions.

Two different types of engines were investigated experimentally: the annular ring cesium contact ion engine and the Penning discharge engine. All testing was performed in a 5 x 15 ft cylindrical metal vacuum test chamber. Rf noise investigations were conducted in the frequency range from 38 to 2200 Mc by employing a stub antenna for rf reception inside the test chamber.

Rf noise tests on annular ring cesium contact ion engines operating up to approximately 132 mA of ion beam current at 5400 V (3.6 mlb of thrust) were made. These tests exhibited no measurable rf beam noise generation; however, noise power was initially observed in the 90 to 300 Mc region due to arcing phenomena around the insulator terminals. This was corrected readily by an improved insulator design. The Penning discharge engine was tested at current levels up to 200 mA (5 mlb of thrust) with a magnetic field ranging from 64 to 160 G. Substantial amounts of noise radiations were observed at the electron cyclotron frequency and agreed within 6% with the calculated values. Noise peaks also were observed at the electron plasma frequency; However, agreement between theory and measurement was marginal in most cases at the plasma frequency.

## II. ANALYTICAL STUDIES

### A. TYPES OF NOISE

Rf noise generated by plasma engines may be subdivided into two main categories: (a) noise common to all plasma engines, and (b) noise occurring only in particular types of engines. These types will now be summarized categorically.

#### 1. Noise Mechanisms Common to All Plasma Engines

##### a. Electron-Ion Collisional Radiation

Electron-ion collisional radiation is referred to as bremsstrahlung<sup>1</sup> and is one of the dominant radiation mechanisms.

##### b. Radiation from Elastic Collisions with Neutral Atoms

Both electrons and ions can collide elastically with neutral atoms. The neutral atoms constitute the background in space (or other engine environment) or are ejected from the plasma engine as nonionized particles.

##### c. Acceleration Radiation

Either ions or electrons or both are accelerated from thermal velocities to higher exhaust velocities by the plasma engine.

##### d. Potential Variation Radiation

Electrons or ions radiate due to acceleration in potential variations in the plasma. These variations are macroscopic and may arise as follows:

(1) Plasma Boundaries — An electron sheath is set up at the edge of the plasma, resulting in a potential well across the plasma. This appears to be one of the dominant noise mechanisms.

(2) Electrostatic Collective Oscillations — Electrostatic collective oscillations include plasma oscillations and plasma boundary ripples.



(3) Mechanical Collective Oscillations -- Mechanical collective oscillations include acoustical waves set up by mechanical vibrations.

(4) Traps -- Traps result as a combination of electrode and particle potentials and arise from different causes in the various plasma engines.

e. Recombination Radiation

Recombination radiation is largely confined to optical frequencies and probably does not interfere with frequencies suitable for communications.

f. Excitation Radiation

Excitation radiation is largely confined to optical frequencies.

g. Cathode Shot Noise

Cathode shot noise arises from random emission of electrons or ions from cathodes. The electron cathode shot noise occurs in all plasma engines, whereas the ion cathode emission may be absent in some engines (Penning engine, for example).

h. Cathode Flicker Noise

Cathode flicker noise varies as the inverse square of frequency and should be negligible beyond audio frequencies.

i. Black-Body Radiation

Black-body radiation arises from hot electrodes or surfaces internal to the plasma engine.

2. Noise Mechanisms in Particular Engines

The engines considered in this study are the cesium contact ion engine, the Penning discharge engine, and the rf engine.

a. Contact Ion Engine

The contact ion engine has no sources of radiation other than those already mentioned. In this engine, trapping is caused by strong potential wells created by the ion beam before neutralization and by potential wells set up by the electrode system.

b. Penning Engine

The internal magnetic field of the Penning engine gives rise to an additional radiation mechanism — cyclotron radiation. Trapping in this engine occurs as a result of magnetic mirror action in the inhomogeneous magnetic field.

c. RF Engine

In the rf engine, rf fields are used to accelerate a plasma. There may be leakage radiation from the power source and from the rf circuit. Also, rf modulation of velocities or densities in the plasma may lead to additional radiation. Power at this frequency is largely coherent and does not constitute noise as such. However, communications systems must discriminate against this frequency. Trapping can occur if the rf wave is synchronous or quasisynchronous with the plasma motion. Ions tend to concentrate in bunches along the wave troughs and so create potential wells.

3. Unimportant Noise Mechanisms

Other noise mechanisms exist which are unimportant for various reasons. These are listed for completeness.

a. Black-Body Radiation from Plasma

The plasma ejected from plasma engines generally is neither optically thick nor in thermal equilibrium. Hence it does not obey the black-body-radiation laws. The various collisional processes considered replace the black-body radiation.

b. Cyclotron Radiation in Space

Magnetic fields in space are of the order of  $10^{-4}$  to  $10^{-5}$  G. Such fields give rise to negligible radiation, since a typical cyclotron radius is much greater than typical plasma beam thicknesses.

c. Cerenkov Radiation

Fast electrons moving through a plasma can give rise to Cerenkov radiation. The required velocities are so large that only a very few electrons can contribute any radiation.

d. Alfvén Waves

Magnetic fields in space are so small that no appreciable Alfvén waves occur. Such waves would set up potential variations in the plasma which would lead to radiation.

B. PLASMA OSCILLATIONS AND NOISE GROWTH MECHANISM

Plasma oscillations are longitudinal body oscillations which do not radiate energy. However, magnetic fields, density fluctuations, and other mechanisms may couple the plasma oscillations to transverse waves, which can radiate energy. The plasma beam ejected from most ion engines consists of essentially monoenergetic ions and of electrons with a spread of velocities. A double stream instability may develop; its exact nature depends on the precise form of the electron velocity distribution relative to that of the ions. In the simplified plasma model considered, conditions near the exhaust plane of a typical ion engine possibly can exhibit this instability; hence, an rf growth of noise may develop. The instability can cause maximum amplification at the electron plasma frequency with a decreasing level of broad-band wave growth as the frequency separation below the plasma frequency is increased. Above the plasma frequency the noise growth drops off very rapidly with frequency.

As shown by Louisell and Pierce,<sup>2</sup> power flow in plasma beam devices exists in two forms of energy — kinetic and electromagnetic. If one considers a conventional plasma in which all the displacement current is in the direction of particle motion, the displacement current is equal and opposite to the convection current. Since there will be no net current flow in this direction the magnetic field will be zero; if the electric field generated by the conversion of longitudinal wave energy of bunched charges is purely longitudinal, the electromagnetic power flow will be zero. This condition of the ion beam downstream from the engine exhaust plane renders it unfavorable for rf noise radiation. In addition,

conditions along the ion beam far downstream are also unfavorable for the existence of instability growth phenomena. This is because the probable thermal velocity distributions of the ions and electrons are superimposed to the extent that the composite velocity distribution does not exhibit the double peaked characteristic shape necessary for the well-known double stream growth mechanism.

When the beam diameter is of the order of a plasma wavelength or less, however, as will be the case in the vicinity of the engine exhaust plane, the plasma stream of space-charge waves appears as a linear source of multiple oscillating dipole charges aligned in the direction of charge flow. This effect exhibits a relatively strong directional field transverse to the beam with a negligible component parallel to the beam; hence, the longitudinal component of the displacement current is negligible. Therefore, since the displacement and convection currents are not equal, electromagnetic power can flow in the form of a surface wave along the plasma outer surface. An approximate theory for a noise growth mechanism is derived in Appendix I. The theory presented for rf generation from a noise growth mechanism on the ion beam indicates that electromagnetic radiation within a neutralized beam will appear over a relatively narrow bandwidth about the electron plasma frequency. This condition will exist if the velocity distributions of the ions and electrons are sufficiently separated that the composite velocity distribution exhibits a double peaked characteristic; this condition may possibly be realized if the ions are assumed to be relatively stationary with respect to the low energy electrons. However, it should be noted that the theory developed here does not take into account the electron velocity distribution but rather has assumed that the electron velocity is single valued. This velocity distribution is not at all well known in present plasma engines.

The results indicate that this type of rf noise would probably interfere with present day space communications receivers which operate with wide open front ends in the vicinity of the electron plasma frequency. However, receivers with command decoder circuits operating with some form of modulation coding probably would not be affected by any beam noise present as long as the selected receiver carrier frequency is different from the plasma frequency.

#### C. DIRECTIONAL EFFECTS ON RADIATION

The collisional radiation is a dipole-type radiation. Acceleration radiation (resulting from plasma engine potentials, electrostatic potential wells, or magnetic mirrors) is also essentially dipole radiation with a well-defined direction. Since the ions normally have a well-defined direction, radiation from them is strongly polarized. Electrons in ion engine beams usually have thermal velocities which are large compared with the net directed velocities and should radiate isotropically. Radiation created inside the plasma engine is collimated by engine geometry in being emitted. Such radiation is strongly directed into the plasma beam and away from the space vehicle and this directivity may be modified by the fields induced upon, and reradiated from, the electrodes.

The plasma acts as a negative dielectric to certain frequencies. The variation of electron density in the plasma beam causes focusing of these frequencies. For the conical plasma beam model (discussed in Section II-D), low frequencies are strongly focused directly away from the space vehicle. Some frequencies can propagate freely through the plasma. Waves of these frequencies are attenuated in propagating through the plasma. The length of the plasma beam is much greater than its thickness; therefore, more radiation escapes in the radial direction than along the plasma beam axis.

The noise power generated by the engine can freely radiate in one direction in the aft hemisphere of the space vehicle. However, an antenna aboard the space ship does not receive all the noise power of the radiation because only a certain portion of the noise is directed toward the antenna. In addition, the antenna radiation pattern must also be considered as a determining factor, depending on whether the antenna exhibits a broad or narrow beam with its respective side lobe level. A conservative estimate of the amount of noise power received at the antenna might be from 20 to 40 dB below the noise power radiated by the engine. The exact amount would be determined primarily by the relative structural geometry of the vehicle between engine source and antenna, as well as by the antenna's radiation pattern.

#### D. PLASMA MODEL

The conditions assumed in the description of a neutral plasma exhaust beam will be discussed. The charged particle density has important effects on noise generated in the plasma, as well as on the noise growth mechanism and plasma directive effects. Thermal effects, instabilities, and microscopic lack of neutralization all cause expansion of the plasma and a resultant density variation. Because of its over-all neutrality, there is no microscopic space-charge spreading of the plasma.

Only thermal expansion is considered here where the mean free path of plasma particles (in the background space gas) is appreciably larger than the initial plasma thickness.

The axial velocity ( $z$  velocity) of the charged plasma particles is established by the voltage characteristics of the engine, and the radial velocity is given by the thermal drift velocity of the ions at the engine exhaust plane. If the plasma expands at constant radial velocity and has uniform density over any cross section, then the proper model of the plasma is a (truncated) cone. This model is justified in Appendix II.

# E. QUANTITATIVE EXAMPLES

A brief summary of the calculations of the expected rf radiation from a typical annular ring cesium contact ion engine will be made for various radiative processes previously discussed for the vicinity of the engine exhaust plane. The engine considered was designed for a perveance of 160 nperv and was operated at approximately 6 kV with a current density of about  $6.2 \text{ mA/cm}^2$ . Table I gives the basic characteristics of possible noise mechanisms.

TABLE I  
Noise Mechanism Characteristics

Noise Mechanism	Noise Power -dBm/Mc	Cutoff Frequency, cps
Electron-Ion Collisional Radiation	153	$0.90 \times 10^{+9}$
Electron Radiation from Plasma Boundary Accelerations	117	$5.65 \times 10^{+9}$
Ion-Neutral Background Collisional Radiation	186	$9.68 \times 10^{+17}$
Neutralizer Cathode Shot Noise Radiation	175	$4.45 \times 10^{+13}$
Ion Acceleration Radiation		
Acceleration Region	207	$1.92 \times 10^{+6}$
Deceleration Region	217	$1.35 \times 10^{+6}$
Black-Body Radiation from Ion Emitter Surface (at 300 Mc for the example)	147	—
Noise Growth Radiation (over a very narrow bandwidth)	100	$0.64 \times 10^{+9}$

The noise power specified in decibels below a milliwatt of power over a megacycle of bandwidth has been calculated with the assumption that the isolation between the noise source and the vehicle's receiving antenna is approximately 15 dB. This is probably conservative for most situations. In most noise mechanisms studied the noise power is a direct function of the beam current. Hence, the expected noise from higher thrust engines will increase proportionately.

In practice, in the rf region of communications there are many sources of noise which might interfere with reception of the radio signal. If all noise sources external to the vehicle are assumed negligible, then the amount of noise in the receiver is that generated only in the receiving circuits. This noise power is the well known  $kTBN$  watts per cycle of bandwidth where  $k$  is Boltzmann's constant,  $T$  the Kelvin temperature,  $B$  the bandwidth, and  $N$  the noise figure of the receiver. At room temperature with a receiver noise figure of about 4 dB the minimum discernible signal level (using conventional techniques) would be approximately  $10^{-14}$  W/Mc or -110 dBm/Mc. Therefore, it is seen in Table I that there are probably only two types of noise which are significant — electron radiation from plasma boundary accelerations and a noise growth mechanism. However, it should be noted that the noise growth mechanism, if it exists, will occur only over a very narrow frequency band about the electron plasma frequency. At frequencies displaced more than 5% from the plasma frequency the noise power level due to the noise growth will be down by more than 20 dB.

### III. EXPERIMENTAL STUDIES

Two different types of engines were investigated — the annular ring cesium contact ion engine and the Penning discharge engine. In an attempt to detect noise generation from a neutralized ion beam in a cylindrical metal vacuum test chamber, a narrow band receiver with a sensitivity of approximately -70 dBm/Mc was employed to perform investigations in the frequency range from 38 to 2200 Mc. A stub



antenna (of length equal to a quarter wavelength at 300 Mc) was employed for rf reception inside the test chamber. This antenna was mounted perpendicular to the cylindrical chamber wall near the engine as shown in Fig. 1. Thus, the antenna was polarized to receive radial transverse electric field cylindrical waveguide modes which are probably the most dominant propagating type modes. However, radiation striking the chamber walls is not completely absorbed (proper space simulation), but is largely reflected. This cavity effect also destroys any directive effects of emitted radiation and leads to an isotropic, homogeneous radiation flux and exhibits large apparent powers in any noise measurements.

Another experimental complication arises from charged particles which impinge on the collector and yield deceleration radiation. In addition, secondary emission of electrons and ions occurs which may interact with the plasma beam and neutral particles to cause additional radiation.

Tests were performed on ion beams with and without neutralizer operation. Investigations were also performed on a pulsed beam in order to isolate the beam from its surrounding electrical environment.

#### A. CONTACT ION ENGINE

Three annular ring electrostatic cesium ion engines were investigated. The designed perveance of these engines was 53, 160, and 202 nperv. A lithium button engine was also investigated which exhibited a perveance of approximately 3 nperv. Results of tests using the two higher perveance engines will be discussed.

The 160 nperv ring engine was operated at 6 kV with a current density of about  $6.2 \text{ mA/cm}^2$  and a beam density of approximately  $4 \times 10^9 \text{ ions/cm}^3$ , yielding about 1.5 mlb of thrust. Initially the noise power observed on this engine was caused by an arcing phenomenon around insulator terminals. However, with an improved engine design

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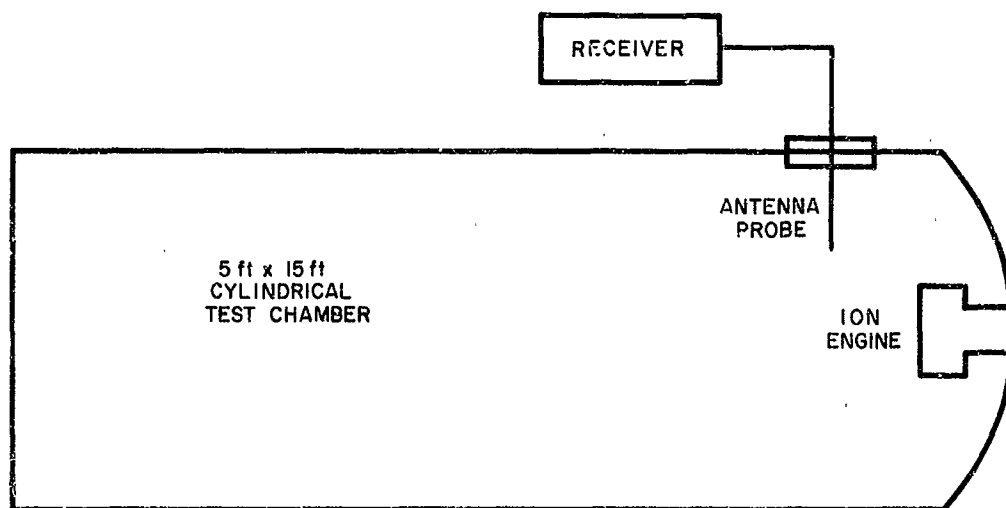


Fig. 1. Test arrangement for noise measurements.

there was no measurable arcing noise power observed on any of the engines tested. In addition, there was no rf beam noise observed over the frequency band from 38 to 2200 Mc down to a power level below -90 dBm/Mc.

The 160 nperv engine was investigated further utilizing an electron neutralizer operated over a dc current range from 0 to 125 mA. No noise power was observed as a function of the neutralizer current in any of the tests. It is felt that this condition exists because the predominant neutralizing agent probably comes from the residual gas within the test chamber.

To reduce proximity effects of the test chamber and to simulate the space environment, the ion beam was also pulsed. The pulse length was kept relatively short compared with the transit time of the ions. The beam was pulsed at 280 pps with 2- and 4-  $\mu$ sec pulses. There was no observable rf noise for the pulse mode of operation except pickup of the modulation envelope of beam pulses.

In an effort to obtain data on engines operating at higher current densities, a high perveance ring engine (202 nperv) was operated with a current density of about  $9.9 \text{ mA/cm}^2$  yielding about 3.5 mlb of thrust. Even though this 0.71-kW beam had considerably more power with increased density over the beams previously investigated, no rf beam noise was observed.

#### B. PENNING DISCHARGE ENGINE

Investigations were performed on an electron bombardment (Penning) engine operating with xenon. The engine was tested under four beam current conditions ranging from 25 to 200 mA; that is, up to about 5 mlb of thrust. The current densities of these engine tests were less than those of the cesium ion engines previously discussed because of the much larger exhaust area employed. All of the pertinent engine parameters are summarized in Table II for each of the four beam current conditions. It can be seen that the calculated and measured rf radiation at the electron cyclotron frequency agree within

TABLE II  
Penning Engine Noise Radiation Data

Beam Current, mA	Voltage, kV	Magnetic Field, G	Density, $10^{15}$ ions/m <sup>3</sup>	Calculated Cyclotron Frequency, Mc	Nearest Measured Radiation Peak, Mc	Calculated Cyclotron Oscillation Power, dBm/Mc	Measured Cyclotron Oscillation Power, dBm/Mc	Calculated Plasma Frequency, Mc	Nearest Measured Radiation Peak, Mc
25	3.5	N.A. <sup>a</sup>	0.422	--	--	--	--	184	195
100	5.0	160	1.405	448	450	-80	-97	336	250
145	4.5	72	2.150	202	190	-87	-95	415	300
200	5.8	64	2.610	179	185	-88	-93	458	450
<sup>a</sup> Not available.									

a few percent and average approximately -90 dBm/Mc. Noise peaks also were observed at the electron plasma frequency; however, agreement between theory and measurement is marginal for the 100- and 145-mA cases. Some of the calculations for the 25-mA case have been deleted because the magnetic field had not been measured. In addition to the above described noise, a few other noise peaks (unexplainable at the present time) were observed over the spectrum. (See Fig. 2.)

### C. NOISE FROM ARCING

Random arcing sources within ion engines, i.e., across insulators, can be eliminated or kept at a tolerable minimum by careful design and assembly. However, such arcing, when it does occur, contributes to rf noise generation. For the sake of completeness in this study report, should other ion engine experimenters experience the noise source, the following data and analysis are presented.

#### 1. Experimental Data

The amount of arcing detected in the experimental tests with contact ion engines was approximately the same on all engines and relatively independent of the amount of leakage current above about 0.5 mA. The frequency spectrum of this radiation covered the band in a periodic fashion from approximately 90 to 300 Mc. A typical spectrum plot is shown in Fig. 3 for two conditions of beam current. As seen from this graph, radiation appears periodically over a relatively small frequency band. The presence of rf energy at various frequencies across the band was not steady or dc in nature; the energy was pulsating at rates from 30 to 120 pulses per minute for different engines at different times. On the plots shown the rate was about 80 pulses per minute. Fourier analysis of this type of spectrum indicates that each arc or discharge across an insulator consists of 5 to 10 pulses over a duration of about 50 mμsec. The pulse phenomenon yielding the observed frequency spectrum may be a characteristic of the type of arc occurring. However, with an improved engine design there was no measurable arcing noise power observed on any of the engines tested.

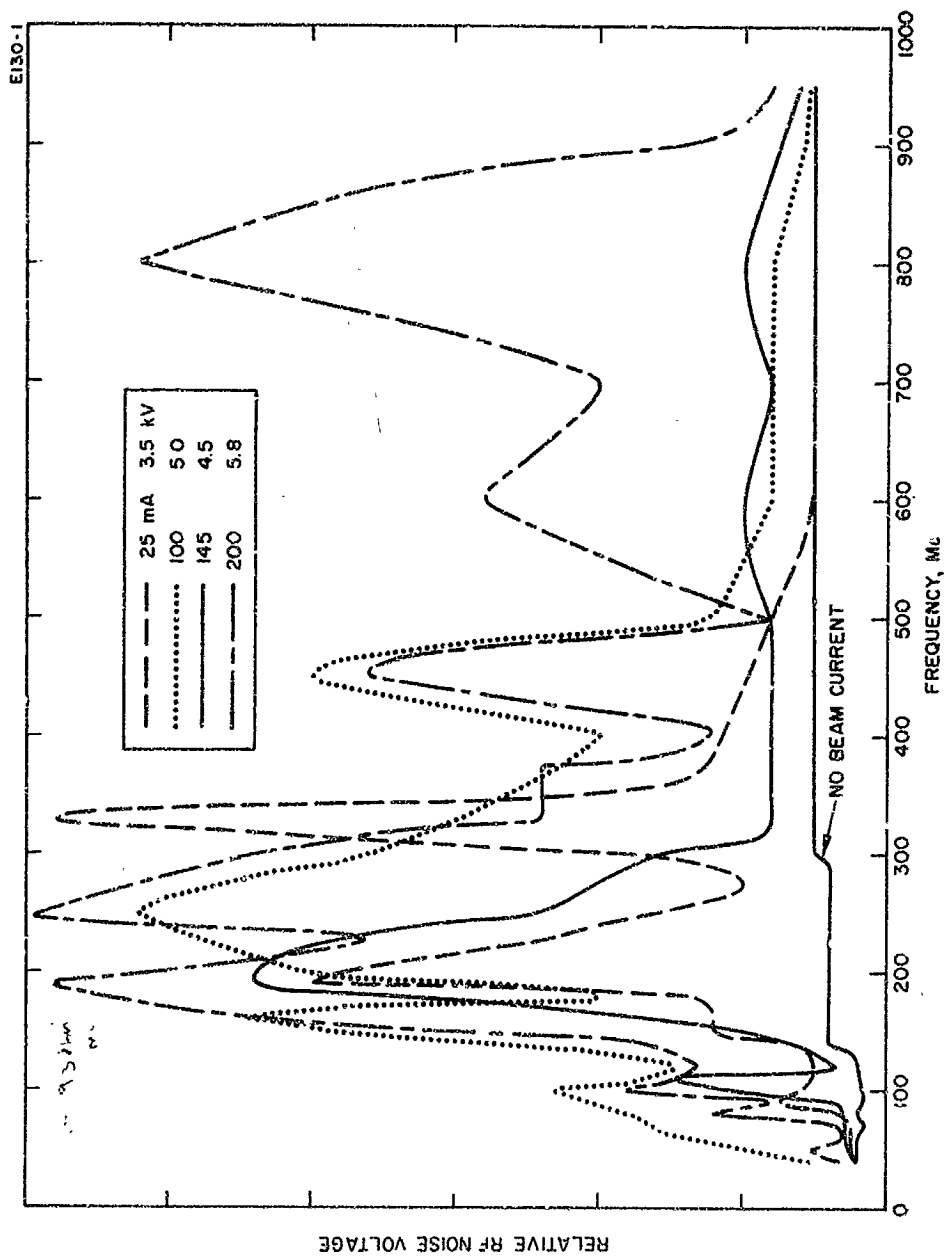


Fig. 2. Noise test data on Penning engine.

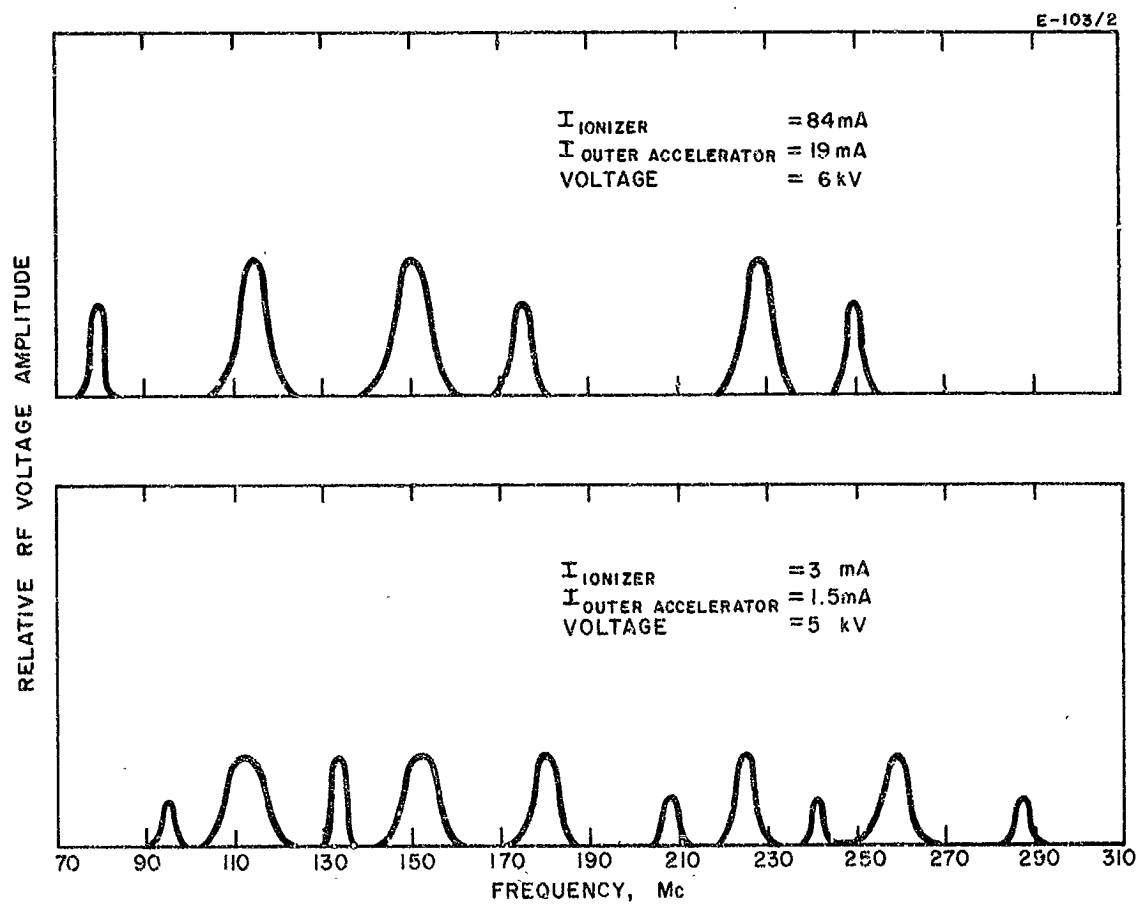


Fig. 3. Noise test data on annular ring cesium ion engine.

## 2. Analysis

### a. Receiver Power

The maximum measured peak receiver power as observed with an oscilloscope was approximately 1 mV across a 50- $\Omega$  input. Hence, the power  $P_r$  at the receiver terminals is

$$P_r = \frac{V^2}{R} = \frac{(1 \times 10^{-3})^2}{50} = 2 \times 10^{-8} \text{ W} \\ = -47 \text{ dBm}.$$

### b. Antenna Gain

The probe antenna was a  $\lambda/4$  stub cut for a center frequency of 300 Mc. If the stub had a gain inside the chamber of approximately +2 dB above an isotropic source at the center frequency, then in the frequency range from 100 to 300 Mc the stub should have exhibited less gain. In considering the wall geometry in relation to the stub it was estimated that the stub exhibited approximately a +1 dB gain over the frequency range of interest.

### c. Cavity Effect

One other parameter must be considered in obtaining a quantitative measure of the power level of the radiation due to arcing. This is the cavity effect. Radiation impinging upon the chamber walls is not completely absorbed but is primarily reflected. To actually simulate the free space condition all of the radiation would have to be absorbed at the wall with no reflection. Hence the radiation energy in the chamber rises to about  $(\sigma/8\omega\epsilon_0)^{1/2}$  times the radiation energy in the same volume in free space. Here,  $\sigma$  is the wall conductivity,  $\epsilon_0$  the permittivity of free space, and  $\omega$  the radian propagation frequency. Assuming a stainless steel chamber at a frequency of 200 Mc the effective gain factor due to this cavity effect is



$$\left( \frac{\sigma}{8 \omega \epsilon_0} \right)^{1/2} = \left( \frac{1.09 \times 10^{+6}}{8 \times 2\pi \times 200 \times 10^{+6} \times 8.85 \times 10^{-12}} \right)^{1/2}$$

$$= 3500 \cong +35 \text{ dB} .$$

In an effort to reduce the cavity effect, which not only gives large apparent powers but also destroys any directive effects of the emitted radiation, various rf absorbing materials were investigated but were not employed because they were too bulky for use in the limited chamber space or too gaseous for normal chamber operation. It should be noted, though, that the cavity effect helps to amplify the low level noise signals, mitigating against the penalty paid.

d. Radiation Source Power

From the above data and calculations the power level of radiation emitted from the arcing source can be quantitatively determined. The power received at the input terminals to the receiver must be modified by the antenna gain and the effective gain factor of the cavity chamber. Therefore, the radiated power from the arc may be obtained as follows:

-47 dBm	Power at Receiver Terminals
- 1 dB	Antenna Gain Reduction
<u>-35 dB</u>	Cavity Effect Reduction
<u>-83 dBm = <math>0.5 \times 10^{-11}</math> W.</u>	

e. Power Received by Space Vehicle Antenna

The noise power generated by arcing around engine terminals can freely radiate in one direction in the aft hemisphere of the space vehicle. However, an antenna aboard the space ship does not receive all the noise power of the radiation because only a certain portion is directed toward the antenna. It can be conservatively estimated that the noise power received at the antenna aboard the space vehicle might be from 20 to 40 dB below that radiated by the engine. The exact

amount would be determined primarily by the relative structural geometry of the vehicle as well as the distance involved between arc source and antenna. In addition, the antenna radiation pattern must also be considered as a determining factor depending on whether the antenna exhibits a broad or narrow beam with its respective side lobe level.

Assuming then that the antenna reduction factor is -20 dB, which would be the case for maximum noise pickup, the power level at the ship's antenna would be approximately  $6.5 \times 10^{-13}$  W or -103 dBm. All power levels stated previously in this section of the report refer to 1 Mc of bandwidth.

In the rf region of communications there are many sources of noise which will interfere with reception of the radio signal. If all external noise sources in the vehicle are assumed very small, then the amount of noise in the receiver is that generated only in the receiving circuits. This noise power is equated as follows:

$$P_n = kTBN \text{ watts/cycle of bandwidth}$$

where

k  $\equiv$  Boltzmann's constant

T  $\equiv$  receiver input noise temperature

B  $\equiv$  receiver input noise bandwidth

N  $\equiv$  receiver noise figure.

Over a 1-Mc bandwidth,  $P_n = 4 \times 10^{-15} N$  W at room temperature. If it is assumed that the receiver has a noise figure of approximately 4 dB ( $N = 2.5$ ), then the minimum discernible signal level would be  $10^{-14}$  W or -110 dBm. A comparison of the power levels due to receiver noise and ion engine arcing noise indicate that the arc noise will be of the same order of magnitude as the basic internal receiver noise.

#### IV. CONCLUSIONS AND RECOMMENDATIONS

Investigations on cesium contact ion engines have exhibited no rf noise from the ion exhaust beam over the 38 to 2200 Mc spectrum at power levels down to -90 dBm/Mc. The engines tested were operated under pulsed and continuous beam conditions, both with and without an electron neutralizer. The only observable noise was that generated early in the program by random arcs across high voltage insulator terminals which produced noise in the 90 to 300 Mc spectrum. This has been rectified by insulator redesign.

Tests of the Penning discharge engine indicate that noise can be expected to radiate in the frequency spectrum near the electron cyclotron and electron plasma frequencies.

Analytical studies of a possible noise growth mechanism over a narrow band about the electron plasma frequency indicate that it may be possible to generate rf interference, although this has not been verified experimentally. Another possible detectable noise source is generation by electron radiation from plasma boundary accelerations. However, the expected power level of this type of radiation probably will be too low to cause interference with present-day receivers.

Several effects reduce the noise from an ion engine seen by a receiver aboard a space vehicle. One major effect is that the plasma appears to radiate as a line source seen almost end on. Many of the noise mechanisms studied have a cutoff frequency at which the noise per cycle bandwidth begins to decrease, either gradually or very sharply. Therefore, reliable communications systems with a vehicle involving a Penning discharge engine should probably be operated above the electron cyclotron and plasma frequencies. In this higher frequency range there is a definite reduction in plasma noise, and the conductive properties of the plasma will have less effect on antenna patterns.

## APPENDIX I

### RF NOISE GROWTH RADIATION FROM A NEUTRAL ION BEAM

#### A. RF PROPAGATION

For electromagnetic power to flow or propagate it is necessary that the subject waves possess a Poynting flux. This requires that the electric field contain a component transverse to the direction of propagation. Hence, the presence of a transverse dc magnetic field in the beam spreading mechanism of the neutralizing electrons within the exhaust plasma of an ion engine might couple the motion of the longitudinally oscillating charge into a direction perpendicular to the longitudinal field. This transport phenomenon would then exhibit a transverse component of the longitudinal electric field. Feinstein and Sen<sup>3</sup> have shown that the ratio of these field intensities in the presence of a static magnetic field may be approximately equated as follows:

$$\frac{E_{\text{transverse}}}{E_{\text{longitudinal}}} \cong \left( \frac{v_z}{c} \right)^2 \left( \frac{\omega_c}{\omega} \right) \quad (1)$$

where

$v_z \equiv$  electron velocity in the longitudinal direction

$c \equiv$  velocity of light in vacuum

$\omega_c \equiv$  cyclotron radian frequency corresponding to the applied magnetic field

$\omega \equiv$  radian frequency of the propagating rf disturbance.

The case with no static magnetic field (as with the ion engines under study) but with a component of mass velocity transverse to the direction of wave propagation gives rise to a corresponding motion on the part of the bunched charge which serves to generate a transverse electric field. The ratio of these field intensities may be approximated as follows<sup>3</sup>:

$$\frac{E_T}{E_L} \approx \left( \frac{v_y v_z}{c Z} \right) = k \left( \frac{v_z}{c} \right)^2 \quad (2)$$

where

$v_y \equiv kv_z \equiv$  transverse component of the electron velocity

$k \equiv$  proportionality constant.

The average electromagnetic power  $S$  radiated from the outer surface of the plasma in the direction of beam flow may be equated as follows:

$$S = \frac{1}{2} E_T H_T = \frac{1}{2} \frac{E_T^2}{Z_0} \quad (3)$$

where  $Z_0$  is the characteristic wave impedance of free space. For the ion engines considered in this analysis, it will be assumed that no dc magnetic field is present. Hence, by combining (2) and (3), a general relationship for the rf power radiated as a function of the longitudinal space charge fluctuation field may be stated as follows:

$$S = \frac{1}{2} \frac{k^2}{Z_0} \left( \frac{v_z}{c} \right)^4 E_L^2 \text{ W/unit area.} \quad (4)$$

Equation (4) indicates that only a very small fraction of the longitudinal fluctuation field energy may be converted into electromagnetic radiation, since for nonrelativistic beams  $v_z/c \ll 1.0$  and for most engines  $k < 1.0$ .

## B. NOISE GROWTH

In the previous discussion equation (4) was derived with no concern as to whether the longitudinal field  $E_L$  exhibited growth. When the value of the relative velocity between ions and electrons in a hot plasma exceeds a certain limit, instability may exist, and growing longitudinal space-charge waves may occur.<sup>4</sup> As the relative velocity is increased beyond this threshold of instability, the growing waves occur first at

long wavelengths since the velocity is small.<sup>5</sup> However, exponentially growing waves cannot exist unless the derivative of the composite velocity distribution of the charged plasma particles has more than one zero. This is the well-known two-stream growth mechanism. Hence, for the purpose of discussion it can be assumed that the ions are stationary relative to the low-energy neutralizing electrons with velocity  $v_z$ ; the wavelength  $2\pi/\beta$  of the fluctuations and their frequency  $\omega$  (possibly complex) obey the simplified dispersion relation

$$\frac{\omega_{pi}^2}{\omega^2} + \frac{\omega_{pe}^2}{(\beta v_z - \omega)^2} = 1 \quad (5)$$

where  $\omega_{pi}$  and  $\omega_{pe}$  are the ion and electron radian plasma frequencies, respectively. In an effort to simplify the mathematical solution, eq. (5) is written with the assumption that the electrons are monoenergetic. This assumption may be justified since the velocity distributions of the ions and electrons are well separated. From this equation, the growth rate of longitudinal fluctuations maximizes at the electron plasma frequency, i. e., when  $\beta v_z = \omega_{pe}$ , as shown by Buneman.<sup>6</sup> The initial coulomb field fluctuation energy will therefore build up exponentially to the level of the directed drift energy. This energy growth will be of a local nature provided the ions and electrons are drifting in the same direction. The initial longitudinal reference coulomb field is as follows<sup>7</sup>:

$$E_o = 1.44 \times 10^{-7} (N)^{2/3} \quad (6)$$

where  $N$  is the electron density. Therefore, the longitudinal field magnitude of the growing oscillation may be obtained from

$$E_L^2 = E_o^2 e^\tau \quad (7)$$

where the growth factor of the fluctuation energy is defined as<sup>7</sup>

$$\tau \equiv \left(\frac{1}{A}\right)^{1/3} \delta \frac{z}{\lambda_p} \quad (8)$$

and

- $A \equiv$  mass number of the ions
- $\lambda_p \equiv$  plasma wavelength
- $z \equiv$  distance downstream which encompasses the local growth disturbance
- $\delta \equiv$  characteristic root of the dispersion equation signifying gain.

Substitution of (7) into (4) yields a final relationship for the amount of rf power radiated by a surface wave generated by a noise growth mechanism. This electromagnetic power then becomes

$$S = \frac{1}{2} \frac{k^2}{Z_0} \left(\frac{v_z}{c}\right)^4 E_0^2 e^\tau \quad (9)$$

Appreciable growth will be exhibited in a relatively narrow frequency band about the electron plasma frequency with quite a noticeable selectivity effect occurring with a corresponding increase in growth. This is graphically illustrated in Fig. 4 for two drift conditions — over distances of 10 and 50 plasma periods. Space permitting, the fluctuation energy can be built up to the level of the drift energy. At this level the maximum growth factor  $\tau_{\max}$  of the fluctuation energy becomes<sup>7</sup>

$$\tau_{\max} = 3 \ln \left[ 20(A)^{2/9} \frac{E}{E_0} \right] \quad (10)$$

where  $E$  is the externally applied field. Thus, the maximum rf power radiated becomes

$$S_{\max} = \frac{1}{2} \frac{k^2}{Z_0} \left(\frac{v_z}{c}\right)^4 E_0^2 e^{(\tau_{\max})} \quad (11)$$

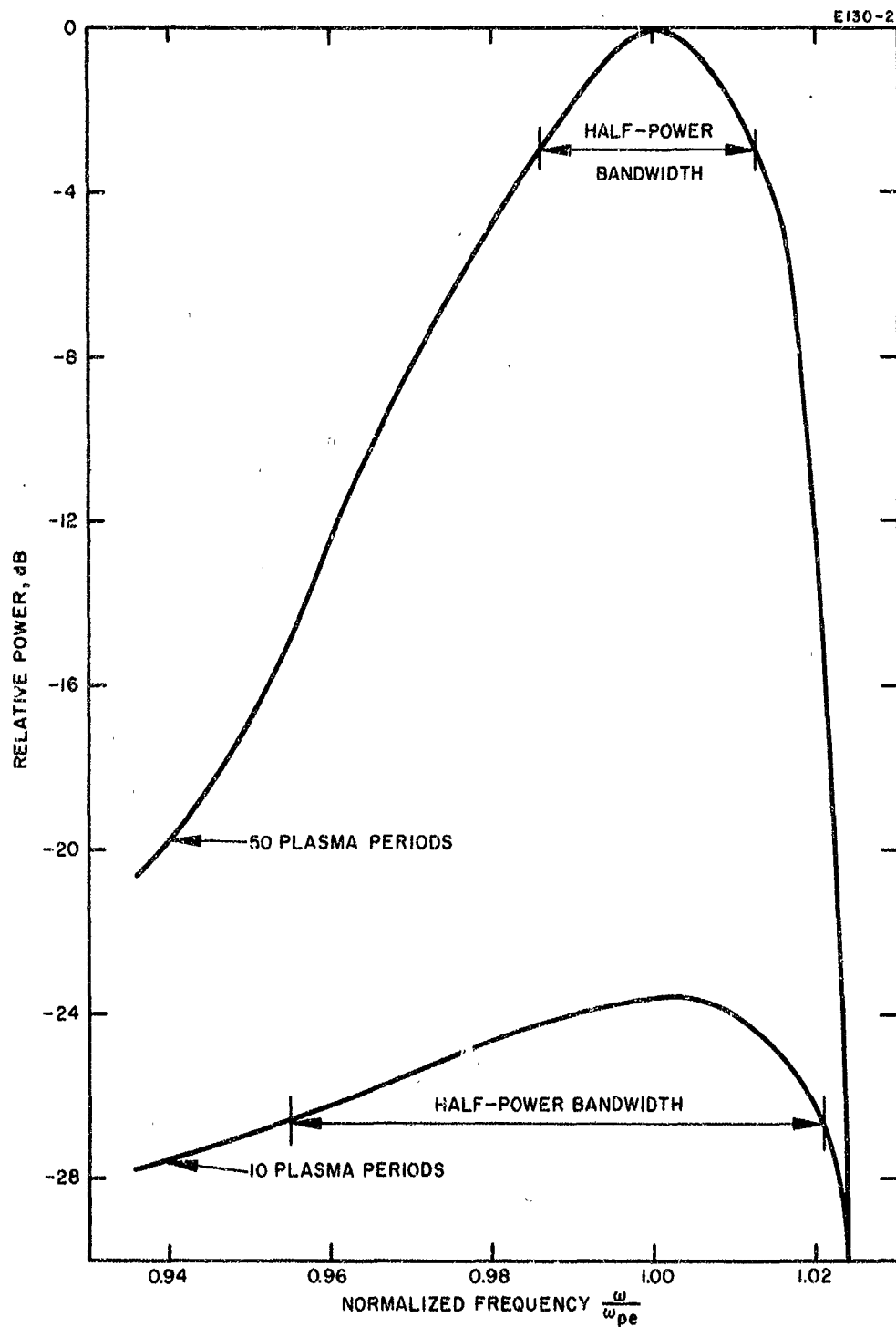


Fig. 4. Relative growth curves as a function of the local drift distance.



## APPENDIX II

### PLASMA WAKE MODEL

Consider first the radial velocity with which a long cylinder of plasma expands. Let the cylinder have initial radius  $r$ , the ions of mass  $M$  have radial velocity  $v$ , and the electrons of mass  $m$  have radial velocity  $v'$ . Ignore collisions. Then, at a later time  $t$ , the plasma is uniformly dense in a cylinder of mean radius  $r + v_0 t$  where, from conservation of momentum and simple geometrical considerations,

$$v_0 = \frac{M}{M+m} v + \frac{m}{M+m} v' \approx v + \frac{m}{M} v'.$$

Ordinarily,  $v \gg \frac{mv'}{M}$  so that  $v_0 \approx v$ , and the plasma expands with nearly the ion radial velocity.

Collisions do not significantly affect the results provided that  $v$  is only slightly changed in a distance  $r$ .

Now consider a Maxwellian distribution of ion radial velocities. The normalized density of particles at a radius  $R$ , after expansion, is approximately given by

$$n(R, t) = \left( \frac{M}{\pi k T} \right)^{1/2} \frac{e^{-MR^2/2kTt}}{2\pi R t}$$

where

$$R \gg r,$$

$$t \gg r \left( \frac{M}{2kT} \right)^{1/2}.$$

Here,  $k$  is Boltzmann's constant and  $T$  is the temperature. Observe that  $v_T = \left( \frac{M}{\pi k T} \right)^{1/2}$  is the transverse part of the ion rms thermal velocity. The normalized number of particles in an incremental area of the cross section is

$$n(R,t)Rdrd\theta = \left(\frac{M}{\pi kT}\right)^{1/2} \frac{e^{-MR^2/2kTt}}{2\pi t} dRd\theta.$$

Essentially, this is independent of  $R$  out to  $R = v_T t$ , and zero thereafter.

These considerations justify a model for the plasma in which the radius grows linearly with time as  $v_T t$  and which has a uniform particle density over its entire cross section.

The situation for the growth of an initial cylindrical plasma is illustrated in Fig. 5. The ions have an axial velocity of  $v_o \gg v_T$ . If  $n_o$  is the initial density at the exhaust plane ( $z = 0$ ), then the density  $n(z)$  is

$$n(z) = n_o \frac{1}{\left(1 + \frac{v_T z}{v_o R}\right)^2}.$$

An "end" can be ascribed to the plasma when the charged particle density reaches the background density  $n_f$ . This gives

$$z_{\max} = \left[ \left( \frac{n_o}{n_f} \right)^{1/2} - 1 \right] \frac{v_o}{v_T} R \approx \left( \frac{n_o}{n_f} \right)^{1/2} \frac{v_o}{v_T} R$$

$$r_{o \max} = \left( \frac{n_o}{n_f} \right)^{1/2} R$$

and a persistence time for the plasma

$$\Delta t = \frac{z_{\max}}{v_o} = \frac{R}{v_T} \left[ \left( \frac{n_o}{n_f} \right)^{1/2} - 1 \right] \approx \frac{R}{v_T} \left( \frac{n_o}{n_f} \right)^{1/2}.$$

The above results apply to a plasma initially cylindrical in shape. If the plasma has an initial annular cross section, then it grows as shown in Fig. 6. After a sufficiently long time, it attains a conical

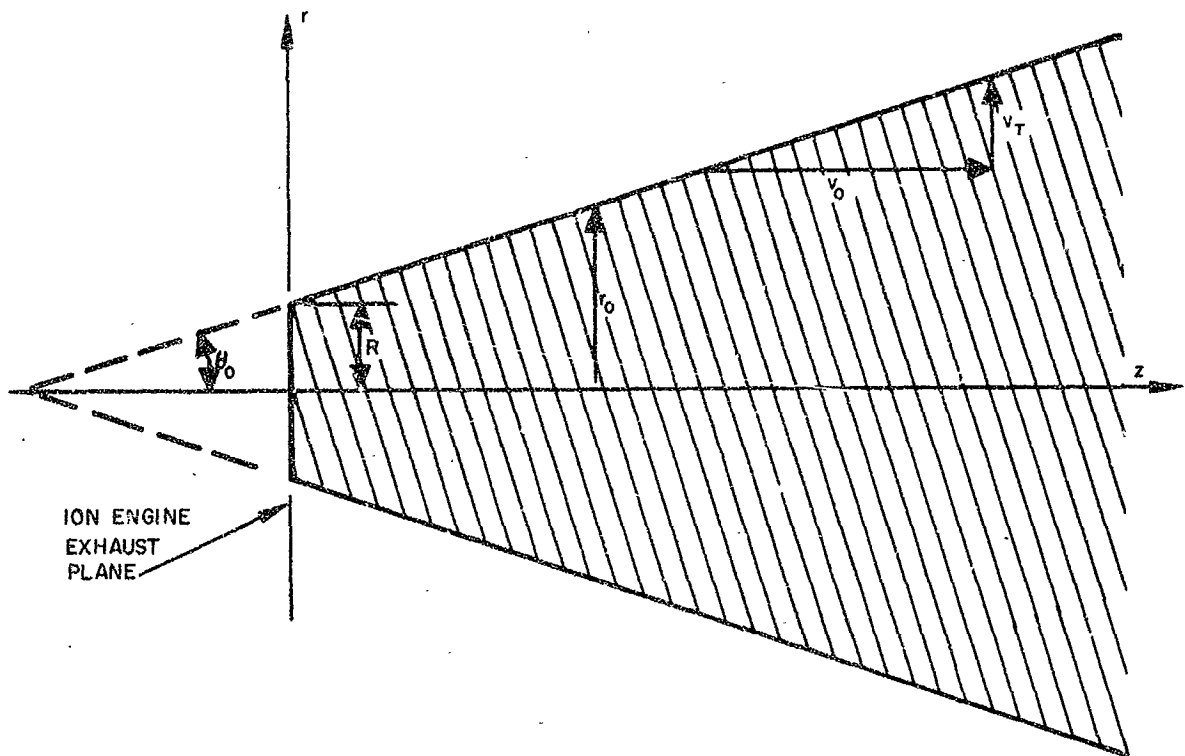


Fig. 5. Cylindrical conical wake model.

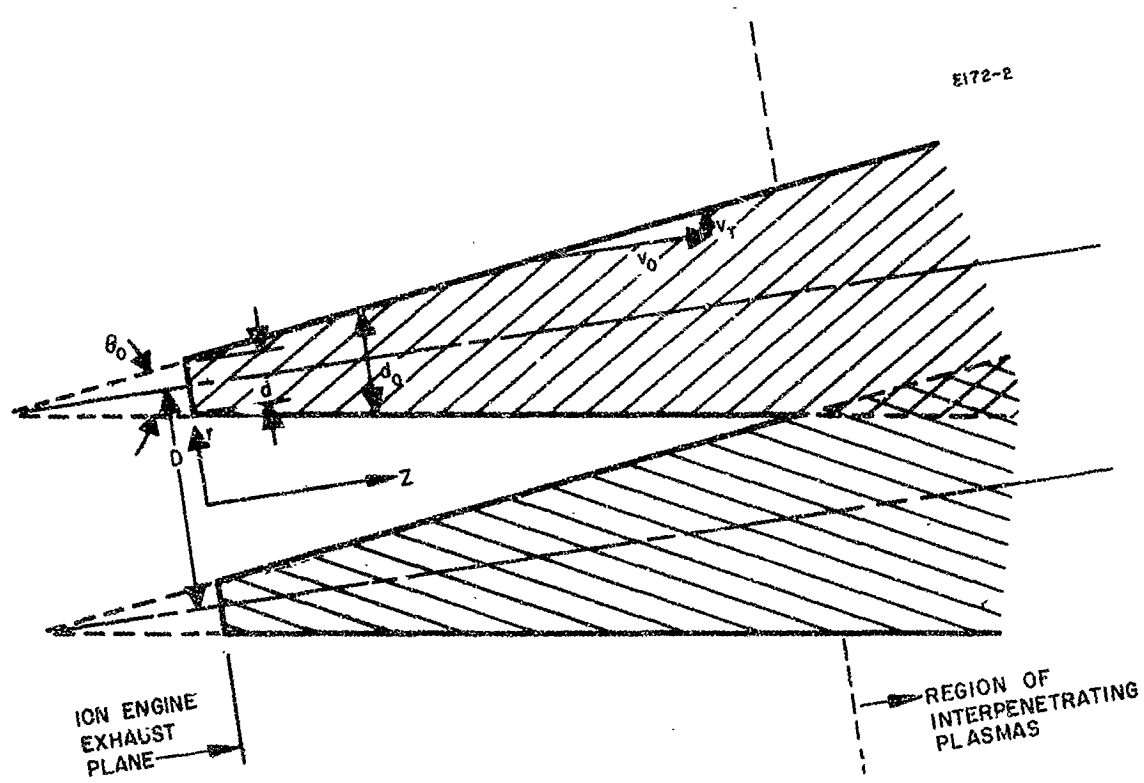


Fig. 6. Annular conical wake model.

outline with almost uniform density so that it approaches the model shown in Fig. 5. The density for this model is asymptotically given by

$$n(z) = n_o \frac{4d}{D} \frac{1}{\left( \frac{1 + 2v_T z}{v_o D} \right)^2} .$$

A cluster of engines merely scales the eventual density by the number of engines.

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